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FINAL REPORT

STRUCTURE AND CONTROL OF THE WALL REGION IN A TURBULENT BOUNDARY LAYER

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Objectives

In the past decade, our group at Cornell has developed a new approach to turbulent flows. This approach uses low dimensional dynamical models to better understand the time dependent behavior of large scale, or energy dominated, features in turbulent and other complex flows. We have applied our approach to the problem of controlling the turbulent boundary layer, with substantial progress. Our objectives as we continue with this effort are:

1. To explore further the control of the boundary layer in turbulent channel flow, refining the control algorithm and bringing more information from the low-dimensional models to bear on the problems of state estimation and control.

2. To make an extensive evaluation of the potential of compliant surfaces for turbulent drag reduction through the use of low-dimensional models and direct simulations of turbulent flow over a compliant surface.

Status of Effort

As part of our effort to understand and control the turbulent boundary layer, we have developed a control strategy based on reduced-order modeling of the large-scale, turbulence-producing structures near the wall. Our control incorporates a state estimation technique, which uses shear stress measurements available at the wall, and has been implemented in simulations of turbulent channel flow, yielding up to 20% drag reduction. In addition to our work with active control, we have begun an effort to explore the possibility of the passive control of the turbulent boundary layer by compliant surfaces. Our

low-dimensional models of the turbulent boundary layer have been adapted to include the effect of the compliant boundary, and we are developing a direct numerical simulation of turbulent channel flow with a compliant boundary using the immersed boundary technique.

Accomplishments

Our group at Cornell has developed a series of low-dimensional models for the turbulent boundary layer which have led to various applications: from reproducing the effects of varying pressure gradients or streamline curvature to providing evidence for the mechanism of polymer drag reduction. However, their greatest promise lies in the areas of design and control. The models yield a reduced description of the dynamics of the near-wall flow, providing insight into the mechanisms of turbulence production and a guide for the development of control algorithms. The focus of our current work has been on (i) the development and validation of the models as tools for the study and control of the boundary layer, (ii) the application of the models to the feedback control of simulations of turbulent channel flow, and (iii) on the computational tools for the extension of the models to more complex flows and the integration of control algorithm development into the modeling framework.

The most energetic coherent structures are extracted from the flow through the use of the Proper Orthogonal, or Karhunen-Loève, Decomposition (POD). The coherent structures are projected onto the Navier-Stokes equations, yielding a system of coupled, nonlinear ordinary differential equations for the evolution of the coherent structures. Previous work has focused on the study of the properties of the models, the use of the models to predict the response of the boundary layer to various physical effects, and control in the setting of the model. Our recent work with the models has focused on their application to active control and on the adaptation of the models to flow over a compliant boundary.

Active Control

We have developed an active control algorithm for near-wall turbulent flow which relies only on information available in practice, namely the shear stress at the wall. An estimation technique developed by Podvin & Lumley [6] has been adapted for the purpose of control and predicts the strength of the two most energetic modes near the wall based on the shear stress at the surface. Using the strength of these modes as an input, our control algorithm employs a switching strategy to suppress the strength of the coherent structures near the wall. The control switches on only when the structures increase in strength and remains off when the structures are weak. The structures are responsible for generating Reynolds stress (and, through the Reynolds stress, drag) in two ways. First, the structures themselves generate much Reynolds stress, and suppressing them will weaken the transport of momentum away from the wall. Secondly, when they are strong, the structures promote instabilities from inflections generated in the mean velocity profile which are also responsible for Reynolds stress near the wall, and weakening the structures

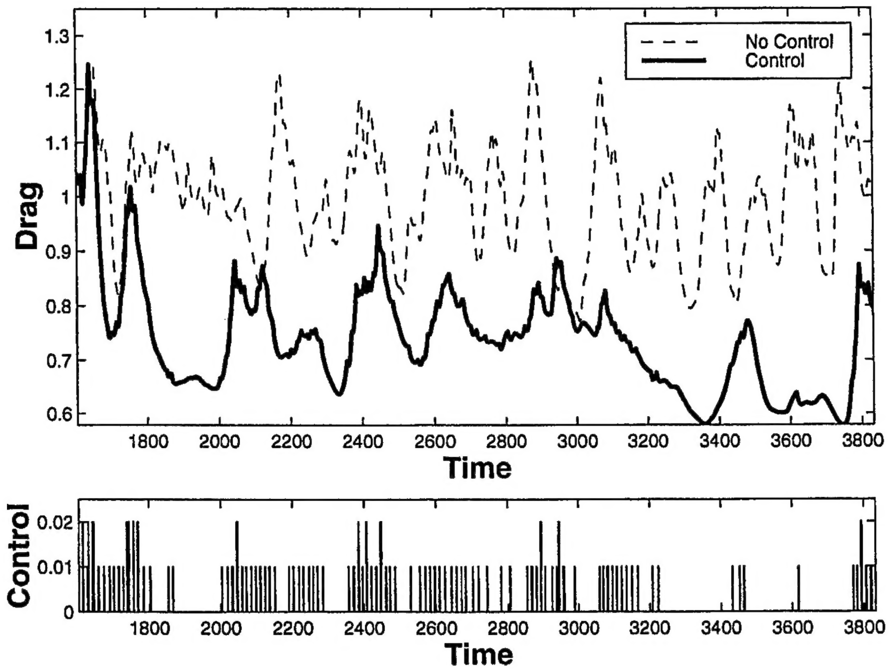

Figure 1: The shear stress (drag) at the wall is substantially reduced by the application of the control (shown in the bottom half of the figure). Note that the control is switched on when the drag is relatively high.

will reduce the frequency of the instabilities. The control influences the flow through a body force applied in the vicinity of the wall. The body force is designed to have the effect of a wall-mounted actuator without including the details of the actuator directly in the simulation. The application of the control in direct simulations of turbulent flow in the minimal flow unit results in a substantial reduction in drag. In a channel with a Reynolds number based on the friction velocity and channel half-height of 100, the drag was reduced by up to 20%. The control was not as successful in a larger channel ($R_\tau = 175$), but still resulted in drag reduction of up to 13%. The control had a significant effect on the quality of the estimation. The co-location of the "sensors" and "actuators" in our simulations created difficulties for our estimation technique: the shear stress at the whole lower wall of the channel was used for the estimates, and the control was also applied over the whole wall. An examination of the eigenfunctions of the flow when the control is applied revealed that the body force induced a cross-flow near the wall which decoupled the shear stress at the wall from the flow away from the wall. However, when the control is switched off, the coupling between the shear stress at the wall and the structures returns and the quality of the estimate improves. In fact, the eigenfunctions of the controlled flow as a whole (sampled both when the control is on and off) have the same form as the eigenfunctions of the uncontrolled flow. It is important when

applying control based on low-dimensional models to apply the control in a manner that is consistent with the underlying basis functions. If the control changes the structure of the flow near the wall (as in control based on distributed blowing and suction which creates a virtual no-penetration layer away from the wall), the estimation technique will break down in the presence of control. We designed our control to closely match the form of the coherent structures so that the dynamics of the flow near the wall would not be drastically altered. Looking forward, we feel that the incorporation of further dynamical information from the models may lead to improvements in the quality of our estimation technique and control in the future.

Compliant Surfaces

Over the past few decades, many studies have focused on the potential for compliant surfaces for drag reduction. Much of this work was motivated by the notion that marine animals possess some form of "natural" drag reduction, following the observations observations by Kramer on the exceptional swimming capabilities of dolphins [4]. A long series of experimental studies that followed attempted to verify the possibility of drag reduction by compliant surfaces in a laboratory setting. However, these studies, summarized by Bushnell, Hefner & Ash [1], did not lead to any reproducible results indicating the possibility of drag reduction. Recently though, Choi *et al.* [2] seem to have been able to in fact reproducibly demonstrate a drag-reducing effect of their compliant surface coating, using a coating whose mechanical properties deviated considerably from the materials used in earlier experiments. In fact, the flow considered by Choi *et al.* was fully turbulent whereas much of the previous work on compliant surfaces focused on transitional flows (applicable to the case of the dolphin).

Our low-dimensional models provide a means of studying the effect of a compliant surface on the turbulent wall layer throughout large regions of the parameter space corresponding to the mechanical properties of the compliant surface. The small size of the models allows for an easy evaluation of the effect of a particular compliant surface on the large-scales of the boundary layer (and through them on the Reynolds stress and drag), while experimental or computational evaluation can be quite costly for a single point in parameter space. As a result, we will identify promising mechanical properties for turbulent drag reduction using the low-dimensional model, and then carefully evaluate the effect of the surface on the structure of the flow using a direct simulation of turbulent channel flow over the complaint surface.

The compliant surface employed by Choi *et al.* was very stiff and exhibited small surface deformations. In fact, the theory which governed their choice of materials suggested that a successful complaint surface should be hydrodynamically smooth — with no deformations of the surface outside of the viscous sublayer. From a practical viewpoint, the restriction of the compliant material to small deformations can considerably simplify the boundary conditions at a compliant surface. While the flow is restricted to move with the compliant boundary, these boundary conditions may be linearized about the undisturbed position of the wall to yield (along with some further assumptions about

the size of gradients which vanish at $y = 0$, e.g. $\partial u_1/\partial x_3$ and $\partial u_2/\partial x_2$):

$$\begin{array}{lcccccc} u_1 & + & U_{1,2}\xi_2 & + & u_{1,2}\xi_2 & = & \dot{\xi}_1 \\ u_2 & & & & & = & \dot{\xi}_2 \\ u_3 & & & + & u_{3,2}\xi_2 & = & \dot{\xi}_3 \end{array} \tag{1}$$

where ξ_i is the displacement of the wall and u_i the fluctuating velocity in the x_i direction, and $U_{1,2}$ is the mean velocity gradient. All of these terms are evaluated at the undisturbed position of the wall $y = 0$. (Note that $U_{1,2}$ is shorthand for $\partial U/\partial x_2$.) This set of boundary conditions should perform well for small disturbances; however, the coupling of fluctuating quantities — $u_{1,2}\xi_2$ for example — will create convolution sums in Fourier space in our low-dimensional models. We can expect these terms to be smaller than the term involving the mean velocity gradient, i.e. $u_{1,2}\xi_2 < U_{1,2}\xi_2$, and will neglect them in our models although we will incur some error as a result. Thus, the boundary conditions become:

$$\begin{array}{lcccc} u_1 & + & U_{1,2}\xi_2 & = & \dot{\xi}_1 \\ u_2 & & & = & \dot{\xi}_2 \\ u_3 & & & = & \dot{\xi}_3 \end{array} \tag{2}$$

Note that if the velocity field is expressed as a linear combination of eigenfunctions $u_i = \sum_{n,k} a_k^{(n)} \phi_{i_k}^{(n)} \exp(ikz)$, the boundary conditions above can be interpreted as a restriction on the combinations of $a_k^{(n)}$, ξ and $\dot{xi}$ which are realizable.

We model the compliant surface as a simple mass-spring-damper system driven by the fluid stress at the wall. In the streamwise and spanwise directions, the deformations of the wall are driven by the shear stress which is easily accessible in the models as a linear term in the model coefficients when the deformations are decomposed into Fourier space:

$$M_w \ddot{\hat{\xi}}_{1_k} + D_w \dot{\hat{\xi}}_{1_k} + K_w \hat{\xi}_{1_k} = \hat{\tau}_{1_k}|_{wall} = \sum_n a_k^{(n)} \phi_{1,2_k}^{(n)} \tag{3}$$

$$M_w \ddot{\hat{\xi}}_{3_k} + D_w \dot{\hat{\xi}}_{3_k} + K_w \hat{\xi}_{3_k} = \hat{\tau}_{3_k}|_{wall} = \sum_n a_k^{(n)} \phi_{3,2_k}^{(n)} \tag{4}$$

(We employ capital letters to describe the properties of the compliant surface for clarity.) The wall-normal deformations of the compliant surface are driven by the pressure fluctuations at the boundary.

$$M_w \ddot{\hat{\xi}}_{1_k} + D_w \dot{\hat{\xi}}_{1_k} + K_w \hat{\xi}_{1_k} = \hat{p}_k|_{wall} \tag{5}$$

Unfortunately, the pressure at the boundary is not as easily accessible in the models as the shear stress.

The pressure at the wall in the models may be determined by examining the Galerkin projection of the pressure gradient term in the models.

$$\begin{aligned} \left\langle -\hat{p}_{k,i}, \phi_{i_k}^{(n)} \right\rangle &= \left(\hat{p}_k \phi_{2_k}^{(n)*}\right)\Big|_{wall}^{\infty} + \int_0^\infty \hat{p}_k \phi_{i,i_k}^{(n)} \, dy & (6) \\ &= \left(\hat{p}_k \phi_{2_k}^{(n)*}\right)\Big|_{wall} & (7) \end{aligned}$$

The eigenfunctions are defined to be divergence free and are non-zero only close to the wall, leaving us only with the pressure term at the wall. As a result, the model equations now have an additional term:

$$\dot{a}_k^{(n)} = \sum_p \left(b_{kp}^{(n)meanvel} + (1+6.28\alpha) b_{kp}^{(n)visc} \right) a_k^{(p)} + \sum_{k',p,q} c_{(k',k-k')pq}^{(n)} a_{k'}^{(p)} a_{k-k'}^{(q)}$$

$$+ \sum_{r,k',p,q} d_{rk'pq}^{(n)} a_k^{(r)} Re \left(a_{k'}^{(p)} a_{k'}^{(q)*} \right) + \frac{1}{\rho} \left(\phi_{2_k}^{(n)*} \hat{p}_k \right) |_{wall} \qquad (8)$$

Our previous models have focused exclusively on the rigid-wall case with $\phi_{2_k}^{(n)} = 0$, so that the pressure term disappears. (If the eigenfunctions are defined only in a region close to the wall, an additional term appears which was incorporated into our previous models as a forcing term. The magnitude of this term is small relative to the others and will be neglected here.) However, to incorporate the compliance of the wall and satisfy the boundary conditions in equation 2, we must include eigenfunctions in our model which are non-zero at the wall.

We choose to base our low-dimensional model for the turbulent boundary layer over a compliant surface on the eigenfunctions of the rigid-walled boundary layer. We will introduce additional eigenfunctions to account for the motion of the compliant surface and allow the boundary conditions to be satisfied. In the absence of surface compliance, our models will revert to the rigid-walled case. Since we do not have an experimental or computational database on the turbulent flow over a compliant surface available, we must derive our additional eigenfunctions in an *ad hoc* fashion. We choose our additional eigenfunctions as solutions of the Stokes equation with periodic motion of the wall:

$$\left(\frac{\partial}{\partial t} - \nu \Delta \right) u = 0 \qquad (9)$$

$$\hat{u}_k(y=0,t) = \cos(\beta t) \qquad (10)$$

where *beta* corresponds to the natural frequency of the compliant surface. The Stokes equation for the streamfunction ψ is employed to determine the additional eigenfunction for the wall-normal motion of the compliant surface. In this manner, we generate three additional eigenfunctions — one for each direction of surface motion — and then orthogonalize them with respect to each other and the rigid-walled eigenfunctions and normalize them.

We now have a set of evolution equations for the coefficients of the eigenfunctions as well as evolution equations for the motion of the wall and the simplified boundary conditions. We choose to determine the coefficients for the additional eigenfunctions from the boundary conditions at the wall. If only one or at most two eigenfunctions has a particular component which is non-zero at the wall, these coefficients may be found easily. The pressure may then be determined from the evolution equation for the

additional eigenfunction representing the wall-normal motion of the wall $\phi_k^{(2)}$:

$$\hat{p}_k\mid_{y=0} \approx \frac{\rho}{\phi_{2_k}^{(2)*}\mid_{y=0}}\left[\dot{a}_k^{(2)} - \sum_p b_{kp}^{(2)} a_k^{(p)} - \sum_{k',p,q} c_{(k',k-k')_{pq}}^{(2)} a_{k'}^{(p)} a_{k-k'}^{(q)}\right] \tag{11}$$

The cubic terms disappear because this additional eigenfunction is defined to have no streamwise component, and there is no streamwise variation in our model. When this expression is substituted into the equation for the wall-normal motion of the wall, the time derivative term merges into the $\ddot{\xi}_{2_k}$ term resulting in an new effective mass of the wall $\tilde{M}_w$. (In fact, $\ddot{\xi}_{2_k} = a_k^{(2)}\phi_{2_k}^{(2)}$ since $\phi^{(2)}$ is the only eigenfunction with a non-zero vertical velocity at the wall.) Normalizing be this new mass results in:

$$\ddot{\hat{\xi}}_{2_k} + \tilde{D}_w\dot{\hat{\xi}}_{2_k} + \tilde{K}_w\hat{\xi}_{2_k} \approx \tilde{\rho}\left[\sum_p b_{kp}^{(2)} a_k^{(p)} + \sum_{k',p,q} c_{(k',k-k')_{pq}}^{(2)} a_{k'}^{(p)} a_{k-k'}^{(q)}\right] \tag{12}$$

Having determined the coefficient and pressure in this way, we have a complete low-dimensional model for the flow over a compliant surface.

$$\dot{a}_k^{(1)} = \sum_p b_{kp}^{(1)} a_k^{(p)} + \sum_{k',p,q} c_{(k',k-k')_{pq}}^{(1)} a_{k'}^{(p)} a_{k-k'}^{(q)} + \sum_{r,k',p,q} d_{rk'pq}^{(1)} a_k^{(r)} Re\left(a_{k'}^{(p)} a_{k'}^{(q)*}\right) \tag{13}$$

$$M_w\ddot{\hat{\xi}}_{1_k} + D_w\dot{\hat{\xi}}_{1_k} + K_w\hat{\xi}_{1_k} = \hat{\tau}_{1_k}|_{wall} = \sum_n a_k^{(n)}\phi_{1,2_k}^{(n)} \tag{14}$$

$$\ddot{\hat{\xi}}_{2_k} + \tilde{D}_w\dot{\hat{\xi}}_{2_k} + \tilde{K}_w\hat{\xi}_{2_k} \approx \tilde{\rho}\left[\sum_p b_{kp}^{(2)} a_k^{(p)} + \sum_{k',p,q} c_{(k',k-k')_{pq}}^{(2)} a_{k'}^{(p)} a_{k-k'}^{(q)}\right] \tag{15}$$

$$M_w\ddot{\hat{\xi}}_{3_k} + D_w\dot{\hat{\xi}}_{3_k} + K_w\hat{\xi}_{3_k} = \hat{\tau}_{3_k}|_{wall} = \sum_n a_k^{(n)}\phi_{3,2_k}^{(n)} \tag{16}$$

$$a_k^{(2)} = \frac{\dot{\hat{\xi}}_{2_k}}{\phi_{2_k}^{(2)}|_{y=0}} \tag{17}$$

$$a_k^{(3)} = \frac{\dot{\hat{\xi}}_{1_k} - \hat{\xi}_{2_k}\frac{\partial U}{\partial y}|_{y=0}}{\phi_{1_k}^{(3)}|_{y=0}} \tag{18}$$

$$a_k^{(4)} = \frac{\dot{\hat{\xi}}_{3_k} - a_k^{(2)}\phi_{3_k}^{(2)}|_{y=0}}{\phi_{3_k}^{(4)}|_{y=0}} \tag{19}$$

We are in the process of using this low-dimensional model to evaluate the potential of compliant surfaces for modification of the dynamics of near-wall turbulence and its resulting effect on the drag at the wall. In addition to our work with the models, we have begun the development of a direct simulation code for simulating turbulent channel flow with a compliant boundary. Because of the complication introduced by the linearized boundary conditions, we have chosen to implement the compliant boundary using the immersed boundary technique which was developed by a previous member of our group [5].

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Publications

Journal Articles

- R. W. Newsome, G. Berkooz and R. Bhaskaran 1998. Use of analytical flow sensitivities in static aeroelasticity. *AIAA Journal* **36**(8):1537–1540.
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Expository Articles, Books and Other Publications

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Interactions

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- P. N. Blossey and J. L. Lumley. Active control of near-wall turbulent flow. Boeing Commercial Airplanes Group, Boeing Corporation, Seattle, WA, October 1998. Invited.
- P. N. Blossey and J. L. Lumley. Active control of near-wall turbulent flow. 51st Annual Meeting of The American Physical Society's Division of Fluid Dynamics, Philadelphia, PA, November 1998. Contributed.
- G. Chini and S. Leibovich. Resonant Interaction of Near-Critical Langmuir Cells and Thermoclinic Internal Waves. 51st Annual Meeting of The American Physical Society's Division of Fluid Dynamics, Philadelphia, PA, November 1998. Contributed.
- P. N. Blossey and J. L. Lumley. Active control of near-wall turbulent flow. Rice University, Houston, TX, December 1998. Invited.
- P. N. Blossey and J. L. Lumley. Active control of near-wall turbulent flow. United Technologies Research Center, East Hartford, CT, January 1999. Invited.
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- P. N. Blossey and J. L. Lumley. Active control of near-wall turbulent flow. Dynamic Systems and Controls Seminar, University of California, San Diego, March 1999. Invited.
- J. L. Lumley and P. N. Blossey. Control of intermittency in near-wall turbulent flow, Isaac Newton Mathematics Institute, Cambridge, UK, June 1999. Invited.

Technology Transitions or Transfer

None.

New Discoveries, Inventions, or Patent Disclosures

None.

Honors/Awards

John Lumley is a Fellow of the American Academy of Arts & Sciences, the American Physical Society, the American Academy of Mechanics, the American Institute of Aeronautics and Astronautics, and was a Guggenheim Fellow from 1973–74.

Sidney Leibovich is a Fellow of the American Academy of Arts & Sciences and the American Physical Society.

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. ABSTRACT (*Maximum 200 words*)

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